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Finite-Element Analysis of the Woodway Landslide, Washington

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By W.Z. Savage,[1] R.L. Baum,[1] M.M. Morrissey,[2] *and* B.P. Arndt[3]

Introduction

The Seattle area has a long history of landslide problems (Tubbs, 1974; Thorsen, 1989; Galster and Laprade, 1991; Gerstel and others, 1997; Baum, Chleborad, and Schuster, 1998). Most landslides occur during winter storms, are typically shallow, initiate in loose surficial materials, and may mobilize into debris flows. However, less common slumps and deep-seated slides cause considerable damage to structures and transportation corridors (Baum, Chleborad, and Schuster, 1998).

Figure 1 shows an oblique aerial view of a large deep-seated landslide that occurred at approximately 10:30 p.m. on January 15, 1997, at Woodway, Washington, 25 km north of downtown Seattle. This slide, which lasted for 15 to 20 seconds, buried railroad tracks at the foot of the bluff under 6 m of debris, derailed a passing southbound freight train, and pushed several rail cars into Puget Sound. Because deep-seated landslides are an important problem in Seattle, the U.S. Geological Survey (USGS) has instrumented the Woodway site to measure rainfall, ground-water pressures, and movement (Baum, Harp, and others, 1998) as part of a larger scale Seattle-area hazards study (Gori and others, 1999). Figure 2 shows an annotated aerial photograph of the borehole locations and instrumentation at the Woodway landslide site.

Arndt (1999) has done a detailed study of the Woodway landslide. His analysis, like other published analyses for deep-seated landslides in the Seattle area (Wilson and Johnson, 1964; Palladino and Peck, 1972; Beuchal and Yamane, 1989; Miller, 1989), established factors of safety with traditional limiting-equilibrium methods (Chowdhury. 1978). We will use the finite-element method to analyze the Woodway landslide.

In what follows, we outline the geology and hydrology of the Woodway landslide site, present geotechnical data for finite-element modeling of initiation of the slide, describe the computational algorithms being used, and present the finite-element modeling results. We finish with a concluding discussion comparing our analysis of the Woodway landslide with that of Arndt (1999) and suggest, from our modeling results, that this landslide occurred because of elevated pore pressures in silt and sand layers in the stratigraphic section at Woodway.

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Geology of the Woodway Landslide Site

The Woodway landslide occurs in Pleistocene glacial deposits. These deposits are often overconsolidated, have a wide range of hydraulic conductivities, are laterally heterogeneous, and form steep, landslide-prone coastal bluffs (Tubbs, 1974; Galster and Laprade, 1991). Figure 3 shows a generalized west-to-east geologic cross section through the Woodway landslide. Vashon till (Qvt), an informal unit of the Vashon Formation, is a low-permeability unsorted mixture of sand, silt, and gravel with occasional cobbles and boulders. Esperance Sand (Qva), a member of the Vashon Formation, consists primarily of permeable sands and silt. Transitional sediments, also an informal unit of the Vashon Formation, (Qtb) are interbedded deposits of hard, sandy to clayey silt, and very dense fine to medium sand with varying amounts of silt. Lawton Clay (Qc), a member of the Vashon Formation, consists of relatively impermeable clays and silts. The pre-Vashon Whidbey Formation (Qw) consists of sands and silts of unspecified permeability. Recessional outwash (Qvr), an informal unit of the Vashon Formation, a mixed sand, silt, and gravel of variable permeability, also occurs at the Woodway site. Because the Recessional outwash and Vashon till are laterally discontinuous at Woodway, both are indicated as the possible top unit in figure 3

As figure 3 is not to scale, a scaled cross section of the Woodway landslide, shown in figure 4, was constructed. The location of this cross section is shown in figure 2. The geology is from Arndt (1999). Note that Recessional outwash replaces Vashon till at the top of this section. The approximate ground

Figure 1. Oblique aerial view of a deep-seated landslide at Woodway, Washington. Photograph taken May 1997 by E. Harp, USGS.

surface before failure in figure 4 is based on the average pre-failure slope from the Edmonds West USGS 1:24,000-scale quadrangle map. The post-failure slope configuration was determined photogrametrically by Arndt (1999).

Hydrology of the Woodway Landslide Site

Resistant and relatively impervious Vashon till caps the higher areas at the Woodway site (Arndt, 1999). Vashon till on hilltops commonly impedes surface water inflow in the Seattle area (Tubbs, 1974; Galster and Laprade, 1991) However, if, as at the Woodway site, the till coverage is locally discontinuous, surface water percolates into the underlying Esperance Sand and continues downward until it reaches the top of the relatively impervious Lawton Clay. Ground water then moves laterally in the Esperance Sand or Transitional beds and emerges as springs on the hillside. If the rate of infiltration exceeds the capacity of the hydraulic gradient to transmit ground water to hillside seeps or colluvium and (or) fill impedes hillside seepage, pore pressures rise and slope failures ensue. For these reasons, many of Seattle’s landslides occur in or near the transitional zone between the Esperance Sand and the underlying Lawton Clay (Tubbs, 1974). Where only colluvium and (or) fill are displaced, the slides usually are shallow and often mobilize into debris flows. Where the Esperance Sand, Transitional beds, and, occasionally, as at Woodway, Lawton Clay or older units fail, the slides are deep seated.

Note in figure 3 the spring occurring at the failure surface a short distance below the contact of the Lawton Clay and the Transitional bed sand. This spring occurs because of seepage from a perched water table within and near the top of the Lawton Clay. Further evidence for this perched water table is provided by the variation of median daily head values, the height to which water rises above pore-pressure transducers PPT 2a and 2b in borehole B2 (see figs. 2 and 3). These variations in median head for the period 9/5/97 to 4/12/00 are shown in figure 5. The water-level fluctuations shown in figure 5 are caused by the annual cycle in barometric pressure. The small negative pressures measured by pore-pressure transducer PPT 2a indicate partially saturated conditions. The porous tip on the sensors has a relatively low air-entry pressure, so negative pressures measured may not be accurate.

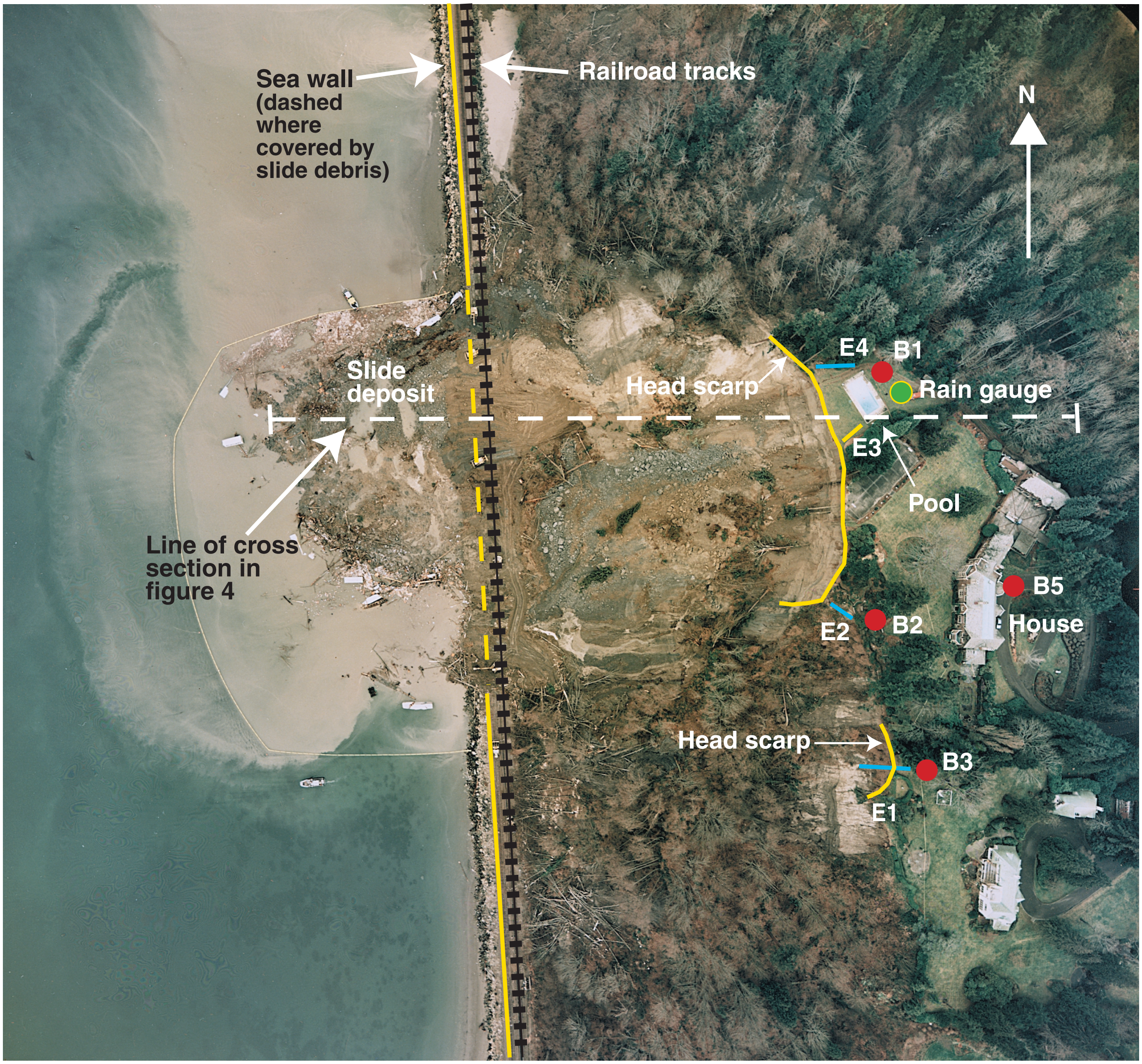


Figure 2. Annotated aerial photograph of the Woodway landslide site (not to scale). Instrumented boreholes are labeled B1, B2, B3, and B5. Extensometers are labeled E1, E2, E3, and E4.

From the data shown in figure 5 it can be inferred that, at the location of borehole B2 (see figs. 2 and 3), a ground-water table of approximately 2.4 m average thickness has been perched near the top of the relatively impervious Lawton Clay since September 1997. Also, pore-pressure transducer data collected since September 1997 at a depth of 28 m in borehole B3 show that at that location (see fig. 2) a ground-water table of approximately 1.2 m average thickness is perched near the top of the relatively impervious Lawton Clay. Because of noisy signals or and other equipment problems, no data are given here for pore-pressure transducers in boreholes B1 and B5.

Geotechnical Properties of Woodway Slide Materials

Seattle-area glacial deposits have wide ranging geotechnical properties. Geotechnical properties we have chosen for the units in figures 3 and 4 are given in table 1. Because of their wide ranges, property values in table 1 are generally average values calculated from a compilation of published geotechnical properties for Seattle-area Pleistocene units (Savage and others, 2000). Strength values for

Table 1. Material properties used in finite-element modeling of the Woodway landslide.

[Dry and wet unit weights are denoted by λ_{dry} and λ_{wet}, hydraulic conductivity by K. σ is Poisson's ratio, E is Young's Modulus, C_p is peak cohesion, and Φ_p is the peak angle of internal friction. All data are in SI metric units of measurement]

Geologic unit	λ_{dry} (kN/m^3)	λ_{wet} (kN/m^3)	K (m/day)	σ	E (MPa)	C_p (kPa)	Φ_p (degrees)
Recessional outwash—Qvr	16	20	50	0.41	225	12	31
Advance outwash—Qva	17	20	50	0.41	270	12	36
Transitional bed silt—Qtb	15	19	0.005	0.49	225	25	25
Transitional bed sand—Qtb	17	20	0.05	0.41	270	30	30
Lawton Clay—Qc	15	19	0.0005	0.49	920	12	24
Whidbey Formation—Qw	17	20	5	0.47	1,000	50	36

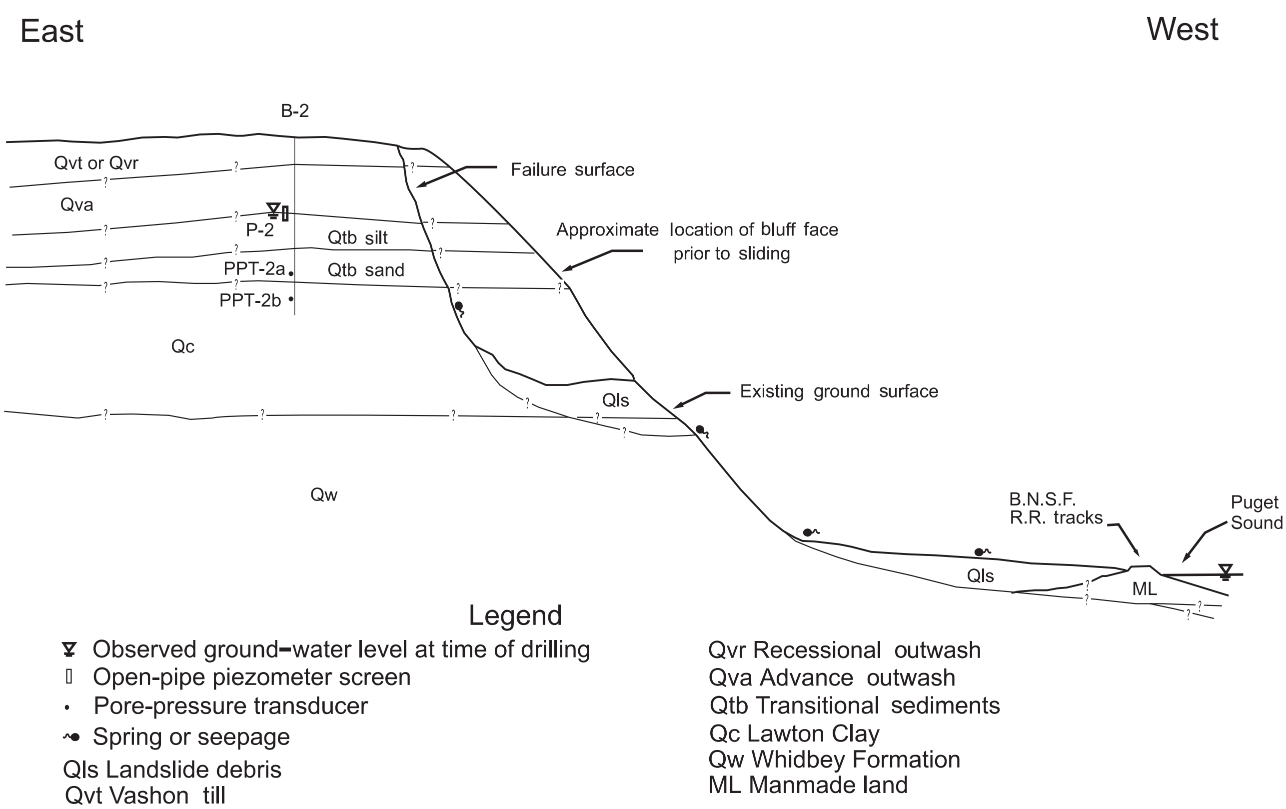


Figure 3. Schematic east-to-west geologic cross section of the Woodway landslide (not to scale). The location of borehole B2 is projected from its location in figure 2. Modified from Landau and Associates (1997).

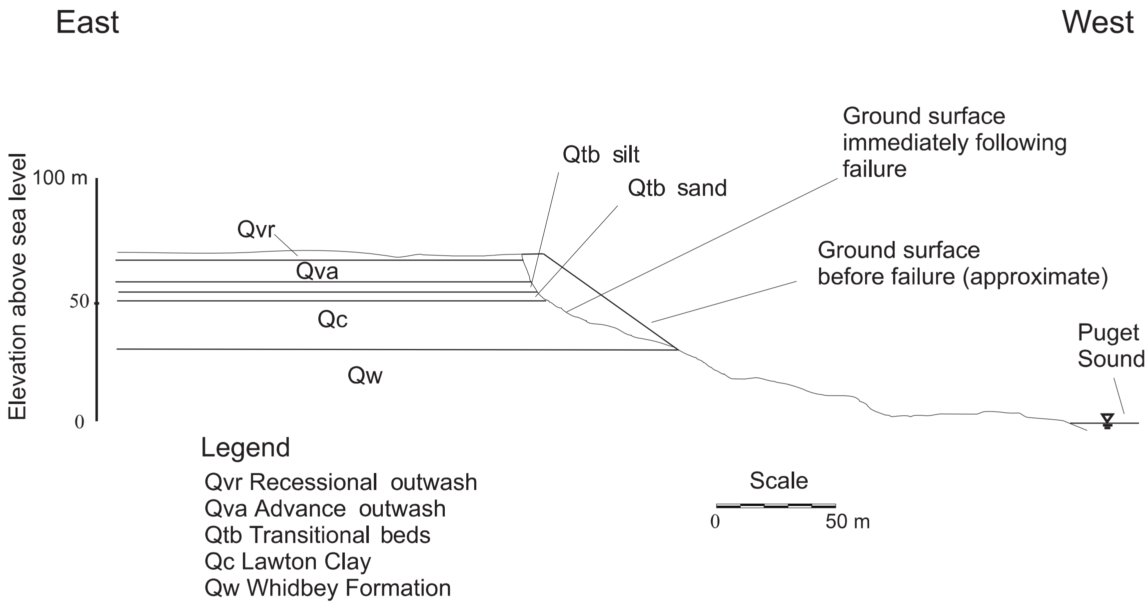


Figure 4. Cross section of the Woodway landslide. The location of this cross section is shown in figure 2. Vertical and horizontal scales are equal.

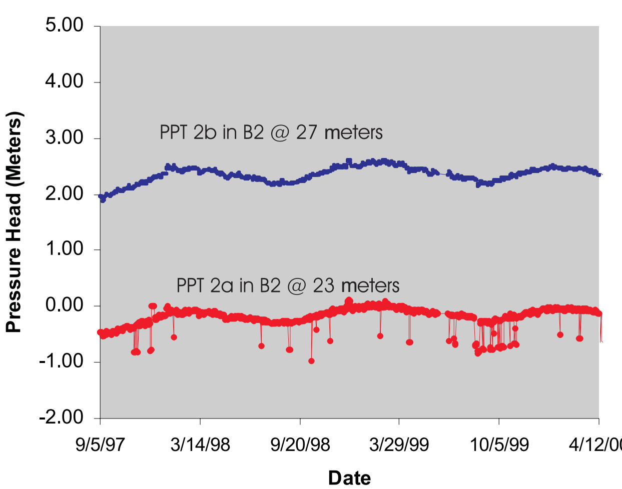


Figure 5. Variation of median daily head above pore-pressure transducers PPT 2a and 2b located at the indicated depths in borehole B2 from 9/5/97 to 4/12/00. Continuously updated plots of these, and other pore-pressure-transducer, rainfall, and extensometer data from the Woodway landslide site are available at http://landslides.usgs.gov/woodway/index.html.

the Lawton Clay are from Arndt's (1999) laboratory tests of samples collected at Woodway and are the values used in his limiting-equilibrium analysis of stability of the landslide. Since published strength data for the Transitional beds are not available, we estimated these properties from properties given for similar materials in Savage and others (2000). Note that, because the Woodway landslide is a new slide, residual strength values were not used in the modeling. Residual strength values would be appropriate if the Woodway landslide were a reactivated slide.

Finite-Element Modeling of the Woodway Landslide

To simulate initiation of the Woodway landslide a finite element analysis was done with Version 7 of the PLAXIS© finite-element program. This program, specifically designed for geotechnical analysis, features automatic mesh generation, pore pressure generation, a robust non-linear elastic-plastic Mohr-Coulomb iterative-solution algorithm, and a phi-c-reduction procedure for calculation of safety factors.

Like conventional slip-circle analyses (Chowdhury, 1978) the phi-c-reduction procedure calculates a safety factor based on comparing the actual strength to the minimum strength required for equilibrium and has been shown (Brinkgreve and Bakker, 1991; Griffiths and Lane, 1999) to give results comparable to conventional methods. The interested reader can find detailed descriptions of the phi-c-reduction procedure in Brinkgreve and Bakker (1991) and Griffiths and Lane (1999).

The finite-element mesh for the pre-slide geometry and geology of Woodway is shown in figure 6*A*. The geometry of the mesh is based on the slope geometry and geology shown

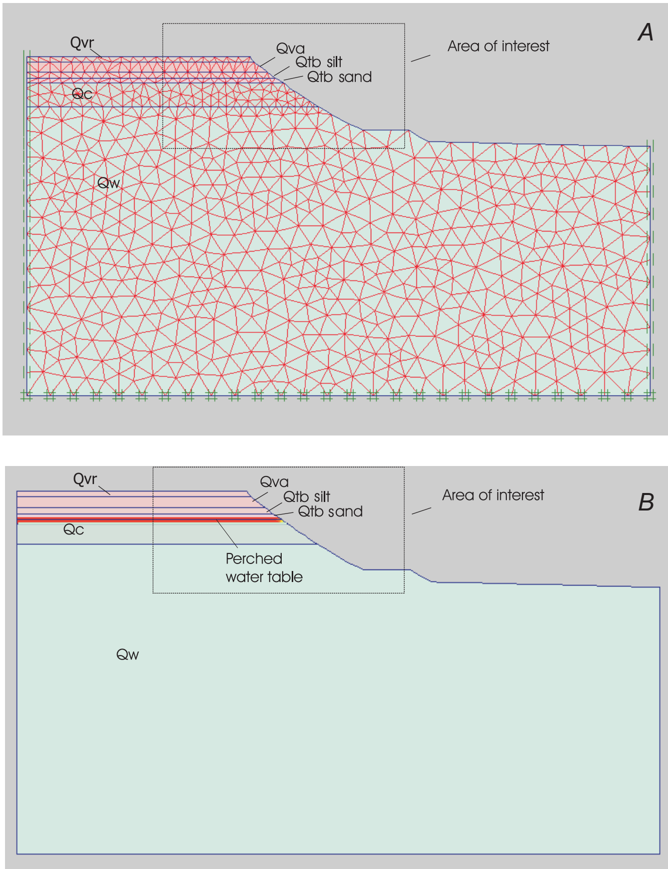


Figure 6. *A*, Finite-element mesh used to simulate the Woodway landslide. *B*, Outline of finite-element model showing the perched water table within and near the top of the Lawton Clay as a shaded overlay. The finite-element mesh and lateral restraint symbols are omitted in figure 6*B* for clarity.

in figure 4. Since mesh refinement was found to lower the factor of safety when material properties and perched water-table height (fig. 6*B*) were held constant, the mesh is refined in the area of potential failure near the face of the bluff. Material properties used for the units in figure 6 are given in table 1.

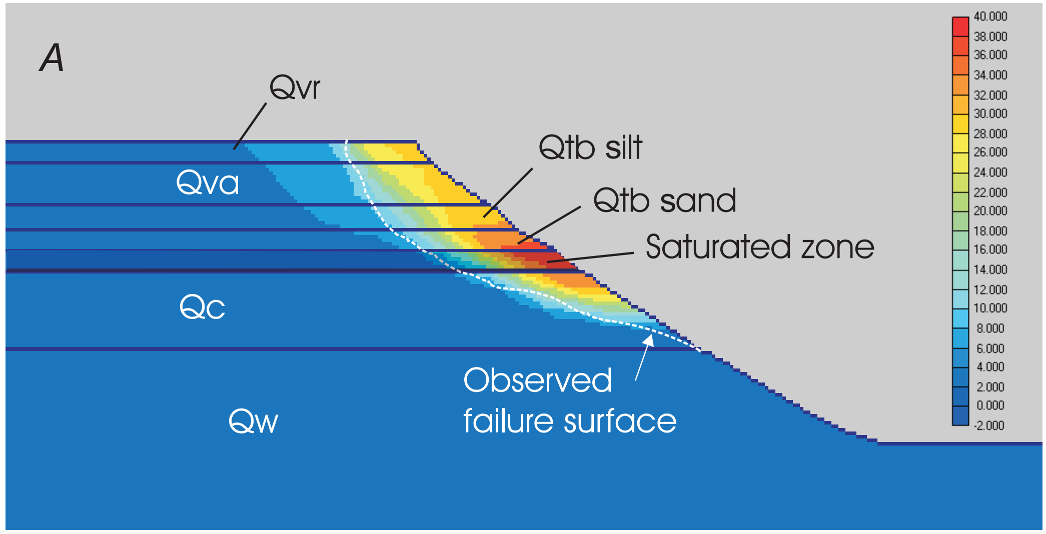
Because the Woodway landslide failed approximately two weeks after heavy precipitation in the Seattle area, it is assumed that rising ground-water levels were responsible for slide initiation. This assumption is supported by precipitation data reported by Chleborad (oral commun., 2000) for the Seattle area. This data shows little precipitation for the 3-day period prior to the event. However, the 18-day precipitation accumulation was approximately 163 mm at the time the Woodway slide occurred—an accumulation at or near Chleborad's (oral commun., 2000) threshold for landslide initiation in the Seattle area.

To simulate the effect of rising ground water on the initiation of the Woodway landslide, the perched water table within and near the top of the relatively impervious Lawton Clay is raised in the finite-element model from zero head to a value that causes the safety factor to approach 1, the value at which failure occurs. Flow in the perched water table is assumed to be horizontal in the finite-element calculation. Thus, equipotential surfaces are vertical and the pressure distribution is everywhere hydrostatic. For dry conditions, the calculated factor of safety is 1.04; for 2-m head it is 1.02; for 4-m head it is 1.01; and for 5-m head the factor of safety is 1.00. The 5-m head elevation puts the top of the perched water table at failure 1 m above the base of the Transitional bed sand (fig. 6*B*).

Predicted displacement magnitudes ($[u_x^2 + u_y^2]^{1/2}$, where u_x and u_y are horizontal and vertical displacements) induced by raising the perched-water-table head from 0 to 2 m are shown in figure 7*A,* and displacement magnitudes induced when the perched-water-table head is increased to 4 m are shown in figure 7*B*. The displacements in figures 7 are calculated by using the elastic-Coulomb plastic algorithm in PLAXIS©. We show only the area of interest outlined in figures 6*A* and 6*B*, because displacements elsewhere are negligible.

Figures 8*A* and 8*B* show deformation of the mesh and concentration of displacements at failure (factor of safety = 1.00) calculated by the PLAXIS© phi-c-reduction procedure. Here the head is 5 m in the perched water table, and it is assumed that Cp = 12 KPa and Φ_p = 24 degrees in the Lawton Clay—the Lawton strength values from Arndt's (1999) laboratory tests used in his limiting-equilibrium analysis of stability of the Woodway landslide. No magnitudes are given for the displacements in figures 8*A* and 8*B* because the phi-c-reduction procedure generates additional, large, unrealistic displacements at failure (Brinkgreve and Bakker, 1991; Griffiths and Lane, 1999). However, the shape of the deformed mesh and the pattern of the displacements give an indication of the shape of the failure surface. It can be seen in figures 8*A* and 8*B* that the predicted failure-surface shape is in reasonable accord with that for the Woodway landslide.

As mentioned earlier, because Seattle-area glacial deposits have wide-ranging geotechnical properties, values used for our finite-element analyses were averages, were estimated, or were values Arndt (1999) used for his limiting-equilibrium analysis of the Woodway landslide. We made these choices because a systematic sensitivity analysis for the Woodway slide would require a large number of combinations of material properties for evaluating the effect of property variation on calculated safety factors. Instead, we calculated factors of safety for the condition that all units had maximum published strength values and the condition that all units had minimum published strength values. Calculated factors of safety for maximum strengths were considerably greater than 1 for all water-table levels above the base of the saturated zone in figure 6*B*. For minimum strengths, calculated factors of safety were less than 1 even when the bluff was dry. After further variation of strength parameters, it was found that the combination of average, estimated, and measured geotechnical properties in table 1 and a 5-m-thick perched water led to the desired factor of safety of 1 for initiation of the Woodway landslide.



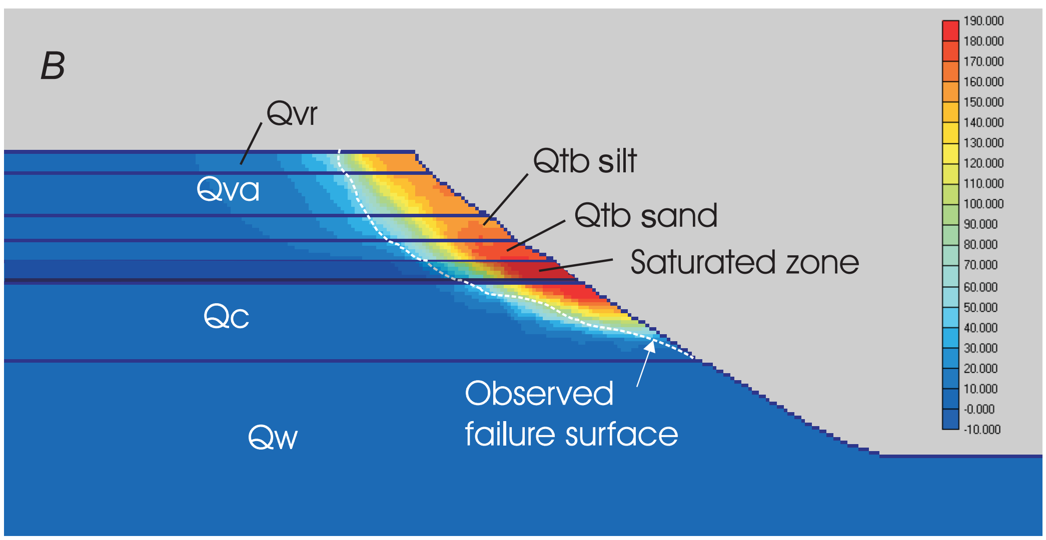


Figure 7. *A*, Predicted displacement magnitudes induced by raising the perched-water-table head from 0 to 2 m. *B*, Predicted displacement magnitudes induced when the perched-water-table head is increased to 4 m. Displacement magnitudes are in millimeters.

Concluding Discussion

As mentioned, Arndt (1999) used the method of limiting equilibrium to analyze the failure of the Woodway landslide. He defined the slip surface for failure analysis by fitting a circular arc to the post-failure ground surface in figure 4 and calculated factors of safety for various ground-water configurations. Arndt (1999) also used a block-failure model for analysis. However, he concluded that the block-failure model was not relevant as it predicted much higher safety factors.

In contrast with the finite-element analysis presented here, Arndt (1999) did not identify the Transitional bed sand and silts in his cross section (figure 28 in Arndt, 1999), preferring to include these layers in the upper Lawton and lower Advance outwash. Also, on the basis of laboratory-measured

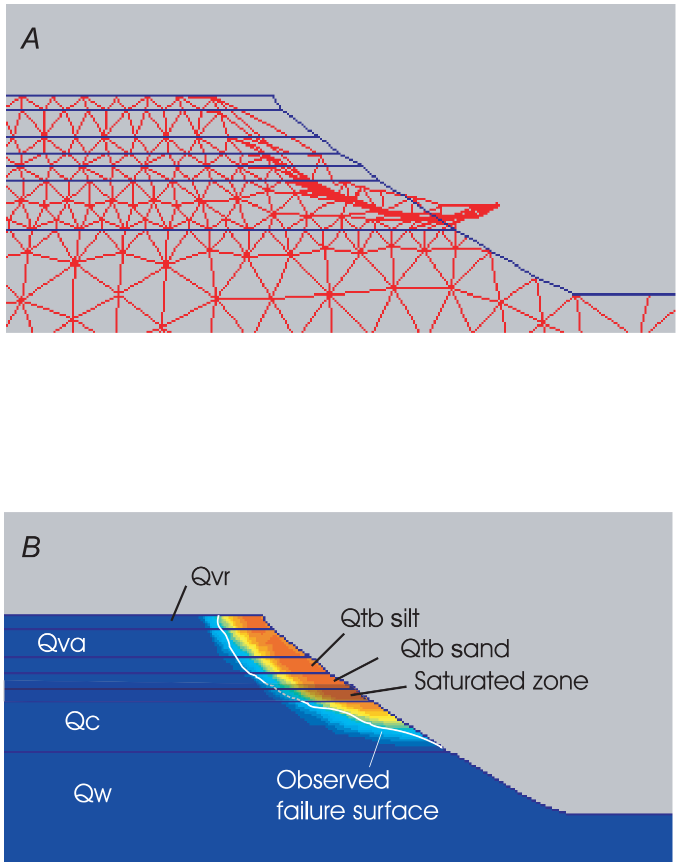


Figure 8. *A*, Deformation of the mesh and *B*, concentration of displacements in regions at incipient failure (factor of safety = 1.00). The perched-water-table head at failure is 5 m, Cp = 12 KPa, and Φ_p = 24 degrees in the Lawton Clay.

strengths, Arndt (1999) divided the Lawton into upper and lower units and placed their contact in the middle of Lawton. As we are using the stratigraphy in figure 3 in the finite-element analysis, we have averaged Arndt's upper and lower Lawton strengths and used the result as our Lawton strength.

Because of the differences in analysis methods, stratigraphic cross sections, and assumed ground-water configurations, computed factors of safety from the two approaches compare only roughly. For dry conditions, the Bishop's circle factor of safety was 1.11 and the finite-element factor of safety was 1.04. A factor of safety of 1.04 was obtained in Arndt's (1999) Bishop's circle analysis when the Recessional and Advance outwash were saturated and the Lawton Clay was dry. To achieve failure by Bishop's circle analysis (factor of safety = 0.98) Arndt kept the upper part of the Lawton dry and completely saturated the Advance outwash and lower Lawton and Whidbey. The finite-element analysis predicted failure when the height of the observed perched ground-water table within and near the top of the Lawton Clay (shown in fig. 6*B*) was increased from current levels to 5 m, that is, to 1 m above the bottom of the Transitional bed sand.

Arndt (1999) suggests that saturation of fractures in the Lawton and saturation in units above the Lawton led to the failure at Woodway. There is field evidence that fractures in the clay have been saturated, making that scenario possible. However, our finite-element results are consistent with the current observed configuration of perched ground water at Woodway and suggest that the slide occurred because of high pore pressures within and near the top of the Lawton Clay and the bottom of the Transitional bed sand.

Although our results suggest that the slope at Woodway failed well in to the Lawton Clay as a result of pore pressures in the Transitional beds, it is difficult to say what pore pressures actually existed at the time of failure. Positive pore pressures probably existed in Transitional beds and the Lawton Clay, but it is likely that the pore-pressure distribution during failure was non-hydrostatic—that is, flow was non-horizontal, particularly near the slope face. Also, fractures in the Lawton Clay may have reduced its strength locally from the peak strengths used in the present finite-element analysis. The effects of non-hydrostatic pore pressures and fracture-induced reductions in Lawton Clay strength should be included in future analyses of stability of the Woodway landslide. Finally, although averaged and estimated geotechnical properties gave reasonable results for the Woodway slide, a more complete sensitivity analysis for evaluating the effect of geotechnical property variation should be done.

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